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Reflection of cold atoms by a cobalt single crystal

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Abstract. We have demonstrated that a cobalt single crystal can be used to make a remarkably smooth retro-reflector for cold paramagnetic atoms. The crystal is cut so that its surface lies in the (0001) plane and the atoms are reflected by the magnetic field above the surface due to the self-organized pattern of magnetic domains in the material. We find that the reflectivity for suitably polarized atoms exceeds 90% and may well be unity. We use the angular spread of a reflected atom cloud to measure the roughness of the mirror. We find that the angular variation of the equivalent hard reflecting surface is $(3.1 \pm 0.3°)$rms for atoms dropped onto the mirror from a height of 2 cm.

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Recent experiments have shown that cold atoms can be conveniently retro-reflected from magnetic structures, either based on microscopic patterns of permanent magnetization [1], or using arrays of small current-carrying wires [2]. When the reflecting surface is curved the mirror can be used to reconstruct clouds of atoms [3], much as a light source can be imaged using geometric optics. When the reflecting surface forms a tube the atoms can be guided [4, 5]. Magnetic mirrors can also be used to make a reflector with adjustable static, oscillating, or moving corrugations [6], reminiscent of a grating in optics. The rapidly developing subject of magnetic atom optics has recently been reviewed by Hinds and Hughes [7]. In this paper, we report on a study of the magnetic field above a cobalt single crystal due to its spontaneous magnetic domain pattern. This field is expected to be strong because the saturation magnetization is high, and this makes cobalt very promising for atom reflection. Our purpose here is twofold: to explore whether a surface with a spontaneously organized magnetic domain pattern can indeed be useful as a tool in atom optics, and to show how atom reflection can provide diagnostic information about a magnetic surface.

The basic idea of the magnetic mirror is essentially the well-known Stern-Gerlach effect in which an atom is accelerated by a magnetic field gradient. In a field of magnitude B the interaction energy is $U = -\mu_\zeta B$, where μ_ζ is the projection of the magnetic moment onto the field direction. In our experiment we use ^{85}Rb atoms in the $(F = 3,\ m_F = 3)$ ground state hyperfine sublevel, which has a negative μ_ζ equal to one Bohr magneton at all laboratory field strengths. These atoms are repelled by the increasing magnetic field as they approach the surface. One simple way [8] to achieve a strong field gradient at height y above a magnetic layer of thickness b is to impose a sinusoidal magnetization on it, say $\boldsymbol{M} = M_0 \cos(kx)\hat{\boldsymbol{y}}$, which gives [7] a field strength $B = \frac{1}{2}\mu_0 M_0 (1 - \mathrm{e}^{-kb})\mathrm{e}^{-ky}$. For a layer that is thick in comparison with the wavelength, this simplifies to $B = \frac{1}{2}\mu_0 M_0 \mathrm{e}^{-ky}$. The important point to note here is that the magnetic interaction potential is flat, depending only on the height above the surface and not at all on the transverse position. This gives a smooth magnetic mirror. When the magnetization pattern also has higher spatial frequency components k', these die away with height more rapidly in accordance with the exponential $\mathrm{e}^{-k'y}$. Thus even a square magnetization pattern produces a smooth reflecting force at a sufficient distance from the surface. By contrast, low spatial frequency components in the magnetization are more important because the fields they produce are not attenuated in this way. These long-wavelength fields interfere with the field of fundamental period k to give a rougher reflector [7]. In this experiment, we explore the spontaneous magnetization pattern of a cobalt crystal and its corresponding roughness as an atom reflector.

1 The cobalt single crystal

The magnetic reflector investigated here is a single cobalt crystal, 10 mm in diameter and 1 mm thick. The surface has been polished and is aligned with the (0001) crystal plane. to better than 1°. Because of its hexagonal crystal structure the magnetic anisotropy is uniaxial, and therefore the magnetization is normal to the surface. This suppresses the formation of domains of closure, allowing a stray field to leak out into the region above the surface. The domains self-organize in order to minimize the contributions of the stray field to the free energy. This results in a quasi-1D domain pattern with alternating magnetization, similar to the early atomic mirrors built from permanent magnets [9, 10], but with a period on the micrometer scale rather than millimeters. Figure 1 shows this domain structure in our cobalt crystal. It is obtained using

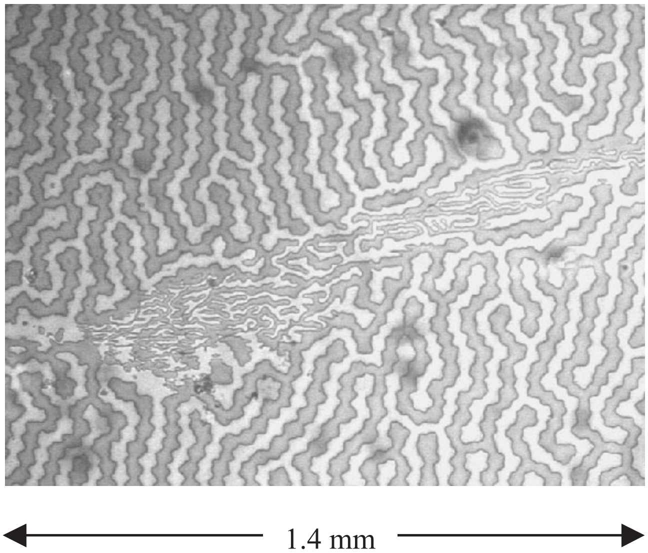

Fig. 1. Microscope image of the magnetic field above the cobalt mirror taken using magneto-optical Kerr effect imaging

a Kerr-effect microscope, in which a thin film of EuS located above the magnetic surface induces a rotation of the optical polarization in accordance with the strength of the field. This picture reveals a remarkable degree of regularity in cobalt, which is much better suited for atom reflection than the Nd-Fe-B structure previously investigated [11]. One sees a striped periodic pattern of domains, with 21 or 22 periods, each of approximately 60 μm width, covering the 1.4 mm width of the picture. This is very reminiscent of the alternating magnetization pattern $M = \cos(kx)$ considered above, although here there are many jumps in phase and small changes of direction,. There are also occasional defects in the surface where the domain structure is disturbed. Figure 1 has been selected to show one of these. They are probably due to scratches on the surface. Above and below this particular defect, the two domain patterns have slightly different average directions.

Ignoring the noise, we can crudely model this as a square-wave magnetic mirror with a fundamental period of $\lambda \approx 60\,\mu\mathrm{m}$ and a field at the surface of $\mu_0 M_0/2 \approx 7\,\mathrm{kG}$, where M_0 is the saturation magnetization of Co. This surface field greatly exceeds the 30 G needed to reflect our rubidium atoms which are dropped onto the mirror from a height of 20 mm. Since the field is expected to decay with distance from the surface according to $\exp(-2\pi y/\lambda)$, the closest approach of the atoms to the surface is expected to be of order 50 μm, where higher harmonic components of the field are very strongly attenuated and the cobalt could act as a relatively smooth reflector for cold atoms. It is less clear from the Kerr microscope picture what role the long wavelength part of the noise spectrum will play, but this image was sufficiently encouraging for us to proceed with an atom reflection experiment in order to find out.

2 The atom reflection experiment

A cloud of $\sim 5 \times 10^6$ ^{85}Rb atoms is collected at the center of a high vacuum chamber in a magneto optical trap (MOT), formed in the usual way [12] by six circularly polarized light beams and a magnetic quadrupole field. The trap is then turned off and the atoms are cooled for 20 ms in optical molasses, which brings their temperature down to $\sim 15\,\mu\mathrm{K}$. This is followed by 2 ms of optical pumping in a small magnetic field (~ 0.2 G) using σ^+ light tuned to the $(^5S_{1/2},\ F = 3) \rightarrow (^5P_{3/2},\ F' = 3)$ transition (together with repumping light to suppress hyperfine pumping). The pumping brings the atoms into the $(F = 3, m_F = 3)$ ground state, which is the one most effectively repelled from strong magnetic field. The atoms are then allowed to fall in the dark towards the cobalt reflector, 20 mm below. After allowing the atom cloud to propagate, we image it in a Princeton Instruments MicroMax 768 CCD camera by illuminating it for 5 ms with a broad standing wave laser beam. This detection beam is approximately horizontal (it is inclined at 18° because of the location of the windows in the vacuum chamber), it has a full width at half maximum (FWHM) of 17 mm vertically, and the peak intensity is $60\,\mu\mathrm{W/cm}^2$. The camera views the light that is scattered horizontally, perpendicular to the detection beam.

From these images, we determine the FWHM of the atom cloud as a function of its free propagation time, as displayed in Fig. 2. Each point is the average of two measurements. No correction was required to account for the intensity variation over the detection beam because the horizontal width we measure almost coincides with the propagation axis of the light. For the first ~ 64 ms, while falling down to the mirror, the cloud expands freely with a transverse velocity distribution $\exp\left(-Mv_x^2/2kT\right)$ due to its thermal energy. The solid line in Fig. 2 shows a least-squares fit to the data using a simple Monte Carlo simulation, which gives an initial cloud size of 1.3 mm FWHM and a temperature of 15.5 μK. At the mirror surface, these parameters yield a cloud width of 6.1 mm, and since the cobalt crystal is of limited diameter (10 mm),

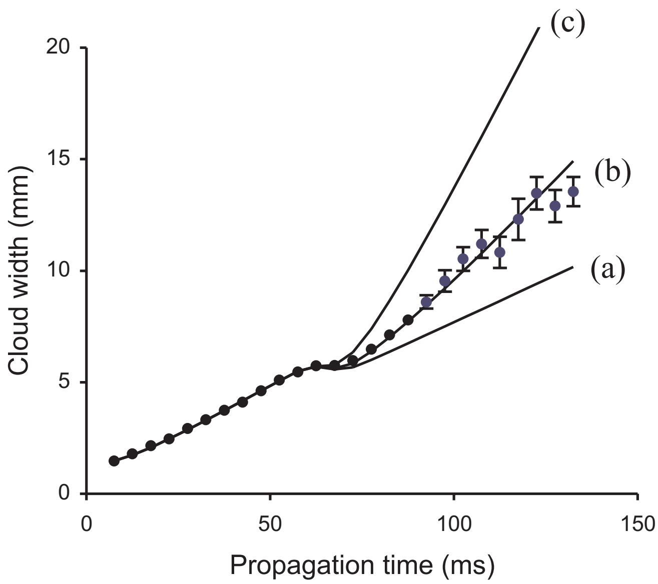

Fig. 2. Width of the atom cloud as a function of propagation time. For the first 64 ms, the cloud expands freely as a result of its initial temperature. The central part the reflects from the mirror, while the outer part continues downwards and is lost. The expansion rate of the reflected cloud is increased by the mirror roughness. *Dots*: experimental data. *Lines*: theory with various values for rms angular variation of the reflectiong surface: (a) 0, (b) 3.1°, (c) 6.2°

the outermost 15% of atoms miss the reflector and are lost from the experiment. Consequently, there is a region in the vicinity of 64 ms where the width of the cloud does not grow. After this, the growth includes both the thermal expansion and the additional expansion due to the roughness of the reflecting potential. This roughness is the quantity of primary interest to us. In our Monte Carlo simulation we treat the reflector as a hard surface, similar to a corrugated tin roof, with height variations as one moves along the x-direction, the direction seen by the camera. Let us call the corresponding variation in the angle of the reflecting surface $\sqrt{2}\sigma\sin(\kappa x)$, which has an rms value of σ. For length scales $1/\kappa$ that are very much smaller than the width covered by the cloud, we find as one would expect, that the cloud size is sensitive to σ but not to κ: the cloud width probes the overall variation of surface angle, but not its spatial distribution. In this region, the theory line in Fig. 2 splits into three. The lowest line shows the predicted cloud width for a reflector that is smooth, and we see that the data are clearly inconsistent with this hypothesis. The middle line represents the best fit to our data in which σ, the only free parameter for fitting this part of the graph, takes on the value $\sigma = 3.1°$. The third line, also incompatible with our data, shows the result of a simulation with twice as much roughness. Our conclusion from this measurement is that $\sigma = (3.1 \pm 0.3°)$ or 54 mrad. This is not the smallest angular spread available: 13 mrad has been achieved with mirrors based on current-carrying wires [13], using the end correction method of Sidorov et al. [9]. The best mirrors have variations of 6 mrad using video tape [3] and 5 mrad with an evanescent wave reflector [14]. The principal advantages of the cobalt mirror are that it has a large surface area, the reflecting potential is the strongest, and it is simple to construct.

The reflectivity of a mirror is another important parameter. Artificial mirrors, made by recording a sine wave on some magnetic storage medium, have been shown to have unit reflectivity for cold atom clouds [1, 3, 15] when a modest bias field is applied perpendicularly to the plane containing the field of the mirror. This is not very surprising because the mirror field has no zeros in the region that is energetically accessible to the atoms, except far away from the surface where the bias field takes over. This ensures that the adiabatic criterion is satisfied. By contrast, it is not at all obvious that the field above the cobalt crystal will be free of zeros. Indeed, we have analyzed the field due to checker-board magnetization patterns with fourfold and sixfold symmetry and there we find atom-mirror interaction potentials which look like egg cartons and have field zeros in every cell. These higher degrees of symmetry seem incapable of producing a flat reflecting potential because of the presence of the field zeros. Inverting the logic, we believe that the remarkable smoothness we have measured for the cobalt mirror in this experiment is in itself strong evidence that the mirror reflectivity must be high. In order to check this argument, we have integrated the images of the atom cloud before and after it hits the mirror and find a ratio of 0.75(5). Since, 15% of the incident atoms miss the mirror, the reflection efficiency is 0.90(5). This includes some loss of atoms that were in the “wrong” magnetic sublevels: $(F = 3, m_F = -3)$ and $(F = 2, m_F \leq 0)$ are not reflected by strong magnetic field. We know from past experiments [1, 15] that this component is typically 10% of the atom cloud and therefore we conclude that the reflectivity for the right magnetic sublevels is consistent with unity and is not less than 90%.

3 Conclusion

We have demonstrated a magnetic mirror for atoms, based on the self-organized magnetic domains in a cobalt crystal. This mirror is a passive element for atom optics which is robust and easy to fabricate and exhibits the most suitable natural domain pattern observed to date for atom reflection. We have shown that it is capable of providing a remarkably smooth reflector for atoms dropped from a height of 2 cm. The surface field of this mirror is expected to be strong enough to reflect atoms with a normal component of velocity up to ~ 10 m/s, although this has yet to be tested in the laboratory. Finally, we have demonstrated that cold atoms reflected from a magnetic surface can provide information about the magnetic domain structure. This seems to us a promising direction for future development.

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